Numerical Simulations of the ICM Radiative MHD Using the MACH Family of Codes

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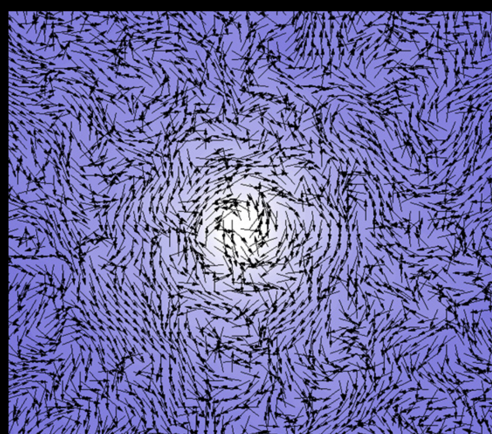
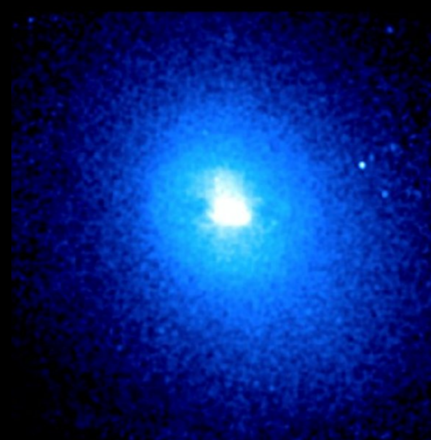
Simulation of Abell 2199
with the MHD code MACH

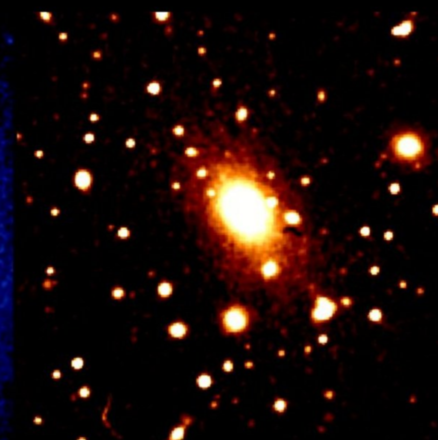


Abell 2199

Chandra (X-ray)



DSS (Optical)



Conference on Turbulence in Cosmic Structure Formation

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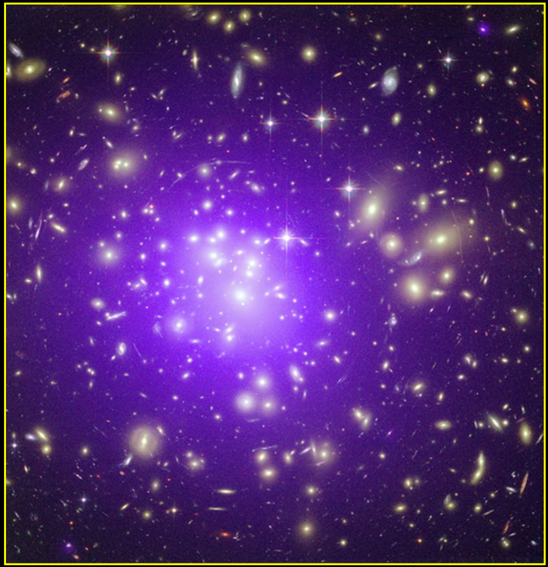
Introduction

- The “cooling flow problem”
  - Galaxy clusters: 5% galaxies, 15% “Intracluster Medium” (ICM), 80% dark matter
  - ICM: diffuse, optically-thin, low-density ($\lesssim$ 0.1 cm^{-3}), hot ($\lesssim$10 keV) X-ray radiating plasma
  - High-resolution X-ray data from *XMM-Newton* and *Chandra* show no evidence that the ICM is significantly cooling. Additional energy source?



Composite image of Abell 1689

- Objectives of this presentation
  1) Introduce **MACH** - a state-of-the-art code with >3 decades of contributions to non-ideal-MHD problems.
  2) Present code validation and first results from 2-D and 3-D simulations of the ICM in a cool-core (CC) galaxy cluster.

Significant progress on the cooling flow problem has been made in the last decade by 3-D simulations - a non-exhaustive review.

- **Parrish *et al*.** [submitted 2012, *MNRAS*] first MHD simulations on the effects of anisotropic viscosity on turbulence and heat transport
  – Conclude viscosity can decrease the linear growth rates of the HBI [**Quataert**, E. 2008, *ApJ*, 673, 758] at small radii in CC clusters, but has less of an effect on its nonlinear saturation. Global simulations show that the HBI robustly inhibits radial thermal conduction leading to a cooling catastrophe. Additional sources of ICM turbulence (e.g. AGN) can suppress the HBI.
- Extensive 3-D simulations of A2199 and other clusters performed with the MHD code *Athena* [**Stone, J. M., *et al*.**, 2008, *ApJS*, 178, 137] by **Parrish *et al*.** [2008, *ApJ*, 677, L9 and 2009, *ApJ*, 703, 96] and **Bogdanović *et al*.** [2009, *ApJ*, 704, 211], and with the MHD code FLASH [http://flash.uchicago.edu], e.g. see **Ruszkowski & Oh** [2010, *ApJ*, 713, 1332].
  – Main conclusion: in the absence of additional physics, thermal conduction alone cannot be responsible for balancing the radiative losses in the ICM, largely due to HBI instability. Additional heating [2009, *ApJ*, 703, 96] or ICM “stirring” [2009, *ApJ*, 703, 96 and 2009, *ApJ*, 704, 211] both possibly caused by a central AGN, were proposed as possible missing mechanisms. Anisotropic viscous effects not included.
- **De Young** [2010, *ApJ*, 710, 743] performed 3-D time-dependent calculations of the evolution of turbulent MHD flows using the eddy-damped, quasi-normal Markov (EDQNM) method and included eddy viscosity.
  – Argued AGN injections are strongly decelerated and become fully-turbulent sonic or subsonic flows due to their interaction with the surrounding medium. Excluded thermal conduction. Suggested presence of AGN stirring can help to disturb magnetic equilibrium; proposed need of MHD simulations that account for both AGN stirring and anisotropic thermal conduction.
- **Dong & Stone** [2009, *ApJ*, 704, 1309] performed 3-D MHD simulations that included anisotropic viscosity to study.
  – Concluded buoyant bubbles are not an effective mechanism for heating the ICM in the central regions of the cluster. Excluded anisotropic thermal conduction.
- **Sijacki & Springel** [2006, *MNRAS*, 371, 1025] performed 3-D smoothed-particle hydrodynamics Navier-Stokes simulations. Excluded magnetic fields.
- **Bruggen *et al*.** [2005, *ApJ*, 630, 740] performed 3-D simulations with FLASH using Adaptive Mesh Refinement.
  – Showed that both viscous and conductive dissipation play an important role in distributing the mechanical energy injected by the AGNs. Excluded self-consistent magnetic fields. Used Spitzer viscosity of unmagnetized plasma with a suppression factor for viscosity and thermal conductivity.
- **Reynolds *et al*.** [2004, *MNRAS*, 357, 242] performed 3-D numerical investigations with ZEUS-MP of the buoyant evolution of AGN-blown cavities in an ICM.
  – Concluded modest level of shear viscosity (~25% of the Spitzer value) can be important in quenching R-T and K-H instabilities that otherwise shred rapidly ICM cavities. Excluded magnetic fields.

The Multi-block Arbitrary Coordinate Hydromagnetics (MACH) Code for Non-ideal MHD, I: Physics

- Time-dependent, 2½-D (MACH2) and 3-D (MACH3) MHD simulation codes [1]
- Resistive-Hall-MHD with Braginskii transport coefficients and various models for anomalous resistivity
- Multi-temperature: electron, ion, radiation (optically-thin/thick and non-equilibrium)
- Quasi-neutral, viscous compressible fluid with elastic-plastic packages
- Analytical or semi-empirical EOS (LANL SESAME tables) and tabular opacities

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

$$\rho \frac{\partial \vec{v}}{\partial t} = -\rho \vec{v} \cdot \nabla \vec{v} - \nabla\left(p + Q + \tfrac{1}{3}\varepsilon_R\right) + \nabla \cdot \boldsymbol{\vec{\sigma}} + \mu_0^{-1}\left(\vec{B} \cdot \nabla \vec{B} - \tfrac{1}{2}\nabla B^2\right) + \rho \vec{g}$$

$$\rho \frac{\partial \varepsilon_e}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_e - p_e \nabla \cdot \vec{v} + \eta J^2 - \vec{J} \cdot \left(\frac{\nabla p_e}{e n_e}\right) + \nabla \cdot (\kappa_e \nabla T_e) - \Phi_{eR} - \rho c_{v_e} \tau_{ei}^{-1}(T_e - T_i)$$

$$\rho \frac{\partial \varepsilon_i}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_i - (p_i + Q)\nabla \cdot \vec{v} + \nabla \cdot (\kappa_i \nabla T_i) + \Phi_{vis} + \rho c_{v_e} \tau_{ei}^{-1}(T_e - T_i)$$

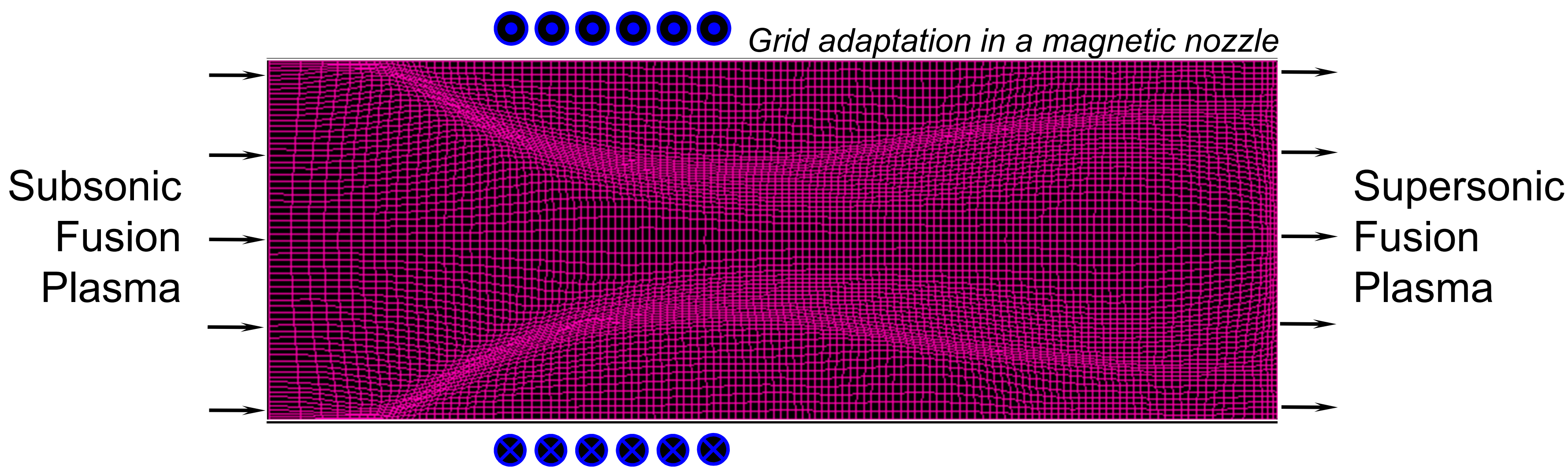
$$\frac{\partial \varepsilon_R}{\partial t} = -\rho \vec{v} \cdot \nabla \varepsilon_R - \tfrac{4}{3}\varepsilon_R \nabla \cdot \vec{v} + \nabla \cdot (\rho \chi_r \nabla \varepsilon_R) + \Phi_{eR}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \nabla \times \left(\eta \vec{J}\right) - \nabla \times \left(\frac{\vec{J} \times \vec{B}}{e n_e}\right) + \nabla \times \left(\frac{\nabla p_e}{e n_e}\right)$$

[1] Peterkin Jr., R. E., Frese, M. H., and Sovinec, C. R. 1998, *J. Comp. Phys.*, 140, 148.

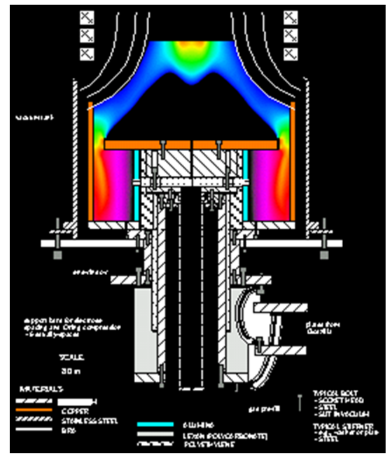
The MACH Code for Non-ideal MHD, II: Numerical Methods & Capabilities

- Finite volume spatial differencing
- Implicit hydrodynamics
- Multigrid implicit magnetic field and thermal diffusion solver
- SOR solver to iterate toward $\nabla\cdot\mathbf{B}=0$ (Brackbill & Barnes, 1980)
- Arbitrary Lagrangian Eulerian (ALE) grid with dynamic adaptation
- MACH2 serial, MACH3 parallel

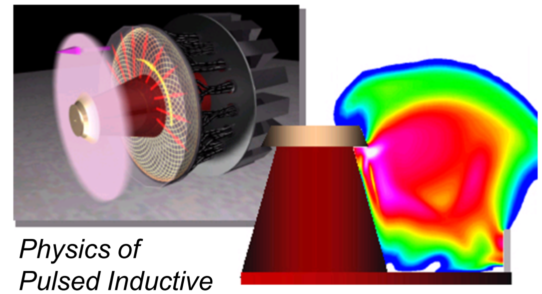


The MACH Code for Non-ideal MHD, III: Background & Applications

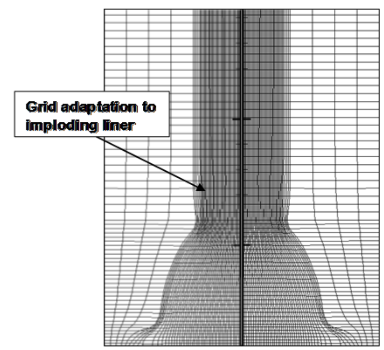
- Developed in the ‘80s at the Center for Plasma Theory and Computation, Air Force Research Lab (Kirtland, AFB) and NumerEx.
- Has been used in the last 30 years to simulate:
  - explosive magnetic generators
  - plasma flow switches
  - inertial-confinement fusion
  - compact toroid schemes
  - Z-pinch implosion physics
  - laser-target interactions
  - high-power plasma sources
  - …
  - plasma propulsion

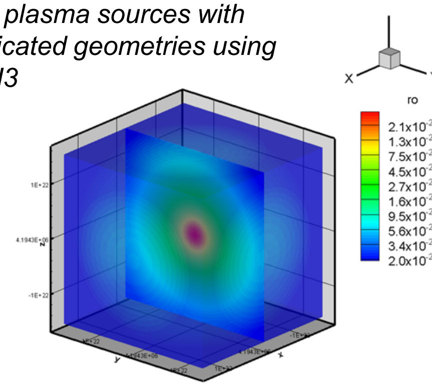


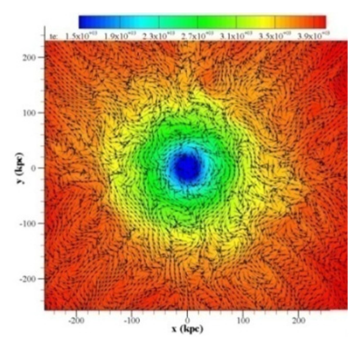
Design of non-ideal-MHD high-power plasma sources with complicated geometries using MACH3



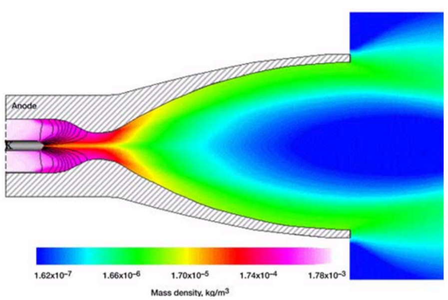
Physics of Pulsed Inductive Thruster (MACH2)

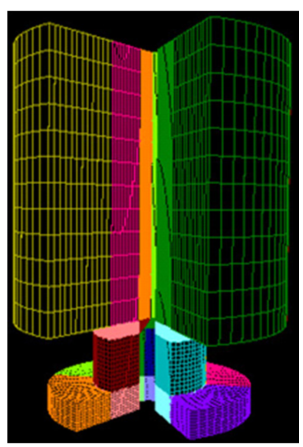






Ideal MHD simulations of the A2199 galaxy cluster with MACH2 & MACH3





Physics of Magnetoplasmadynamic Thrusters (MACH2 & MACH3)

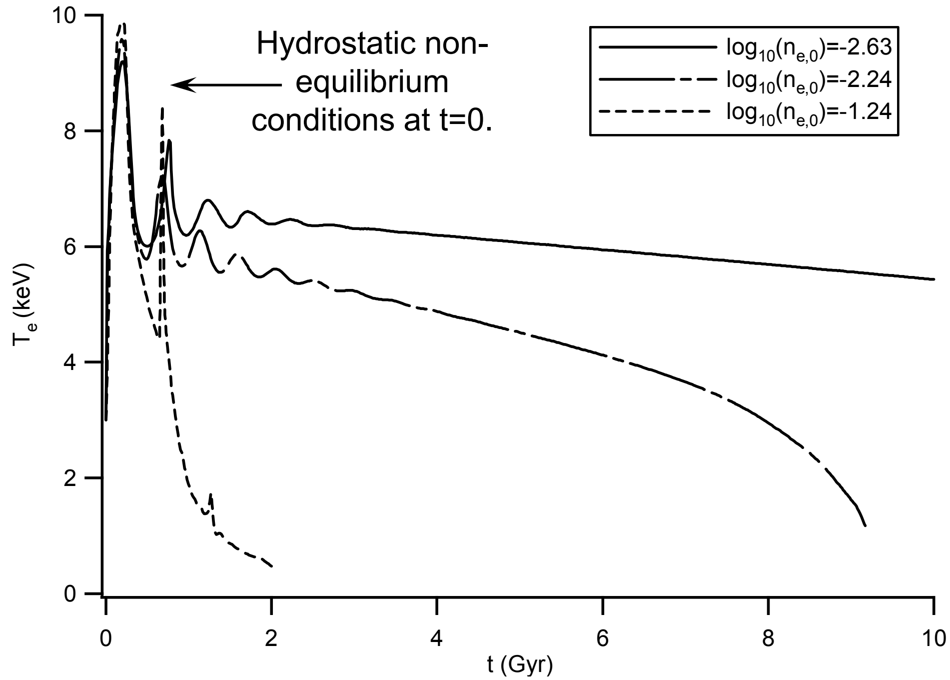
The MACH Code for Non-ideal MHD, IV: Heritage

- Export-controlled code. Used at more than 20 government and academic institutions nationwide since the ‘80s:
  - Air Force Research Laboratory, Kirtland (AFRL)
  - Los Alamos National Laboratory (LANL)
  - Arizona State University (ASU)
  - NASA Glenn Research Center (GRC)
  - University of Washington (UW)
  - Ohio State University (OSU)
  - University of New Mexico (UNM)
  - University of Tennessee Space Institute (UT)
  - Pennsylvania State University (PSU)
  - University Alabama, Huntsville (UAH)
  - Maxwell Technologies Inc.
  - Alameda Sciences Inc.
  - Science Applications International Corporation (SAIC)
  - Titan Pulsed Sciences Division
  - ...
  - and the Jet Propulsion Laboratory (JPL)

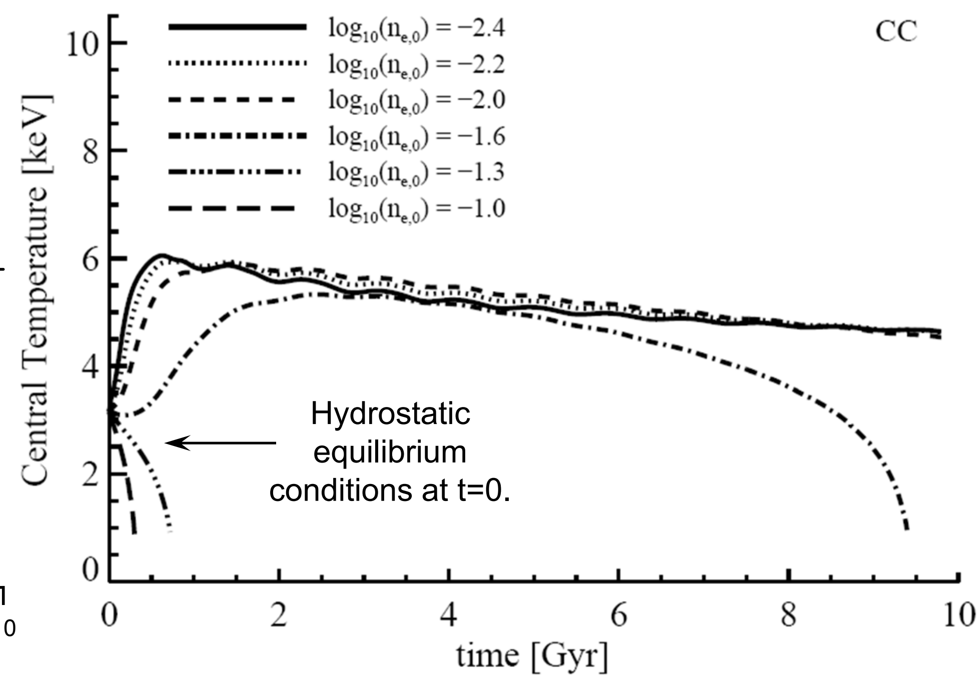
Code extensions and numerical tests at JPL now allow for MACH simulations of the ICM, I.

- Implemented gravitational acceleration due to Navarro-Frenk-White (NFW) profile of dark matter density with “softened” core.
- Validated MACH augmentations with published results.

MACH2 Numerical Tests (**B**=0)



Conroy & Ostriker 1-D Spherical Simulations (2008, *ApJ*, 681, 151), **B**=0



Code Extensions & Numerical Tests, II: Magnetic Fields

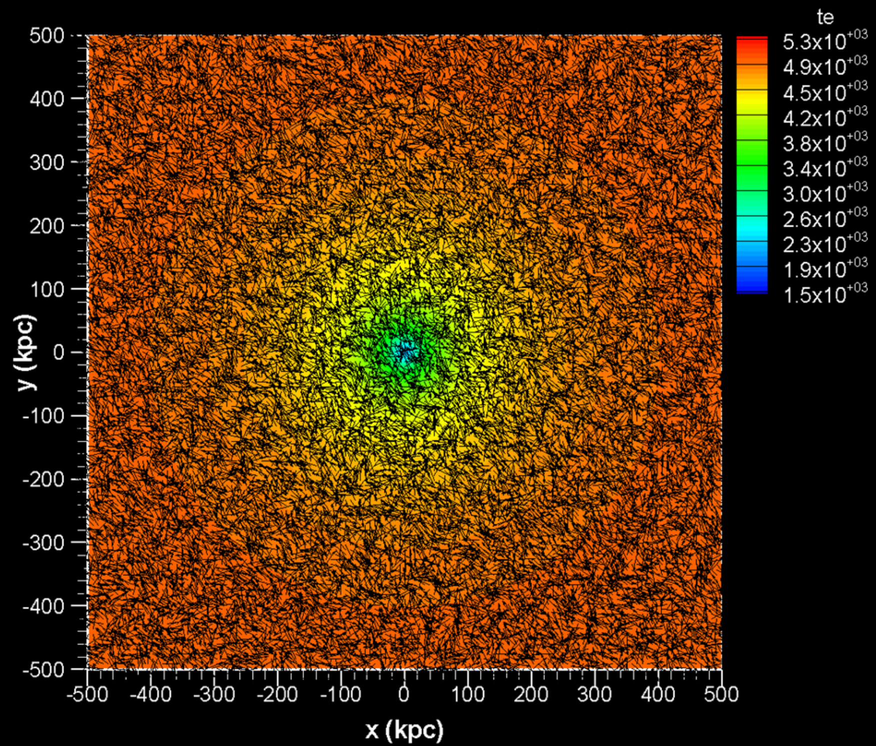
- An already extensive suite of initial conditions for the magnetic field in MACH has been augmented with an option for turbulent (tangled) fields [1]:
  - specify random magnetic fields in **k**-space,

$$B_x(k) = [Re(B_x), Im(B_x)] = [N_1 B, N_2 B]$$
$$B_y(k) = [Re(B_y), Im(B_y)] = [N_3 B, N_4 B]$$

  - perform divergence cleaning in **k**-space,

$$B_i(k) = \left(\delta_{ij} - \frac{k_i k_j}{|k|^2}\right) B_j(k)$$

  - perform complex inverse Fourier transformation in 2-D or 3-D to obtain the real components (**r**-space).



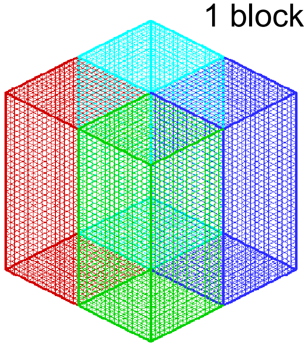
Te overlaid by unit vectors of the magnetic field (t=0, MACH2).

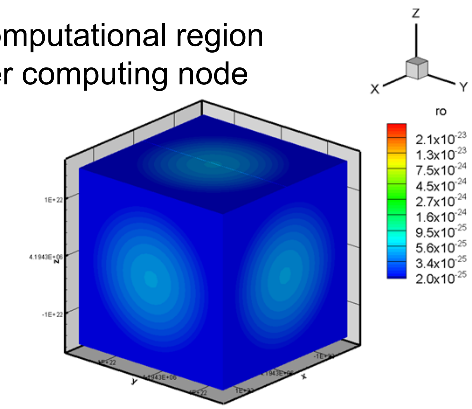
[1] Ruszkowski, M., & Oh, S. P., 2010, *ApJ*, 713, 1332.

Code Extensions & Numerical Tests, III: 3-D

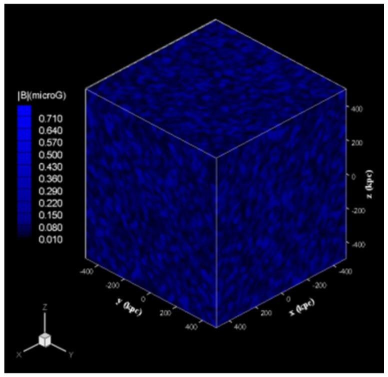
- Multi-block approach in MACH3 allows for easy parallelization on processor clusters.
- MACH3 successfully transferred from ASU, compiled and executed in multi-passing interface (MPI) mode at JPL.
  - Results verified by numerical tests and comparisons.

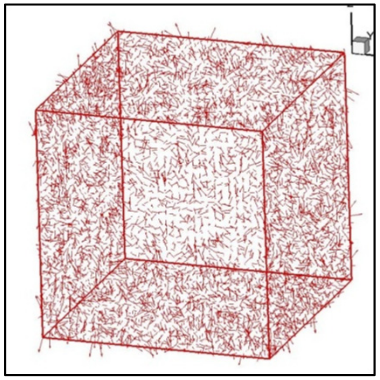
4-block computational region
1 block per computing node





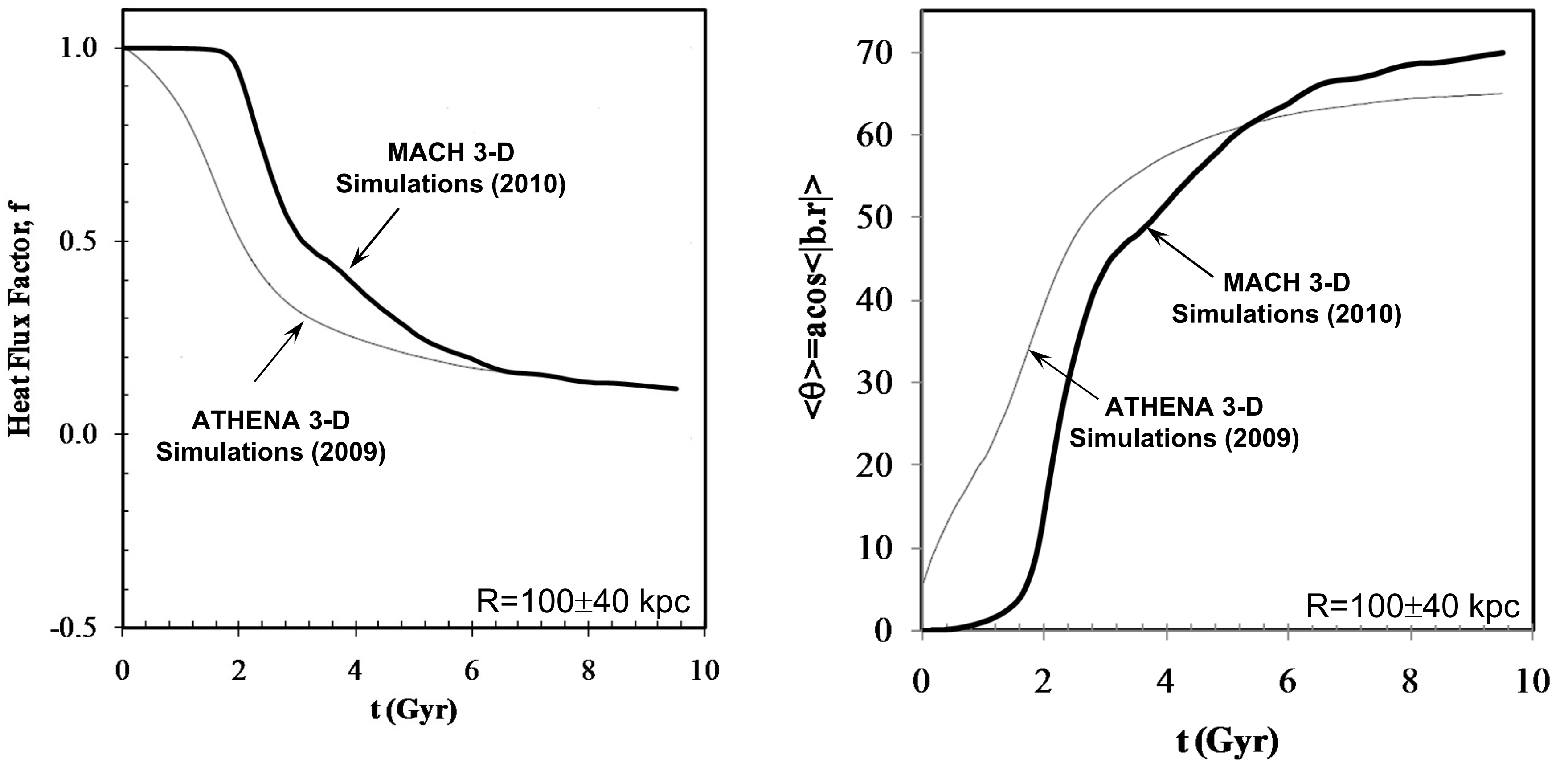
Initial condition for turbulent magnetic field in MACH3





MACH3 MHD simulations reproduce published results but solution sensitive to initial state.

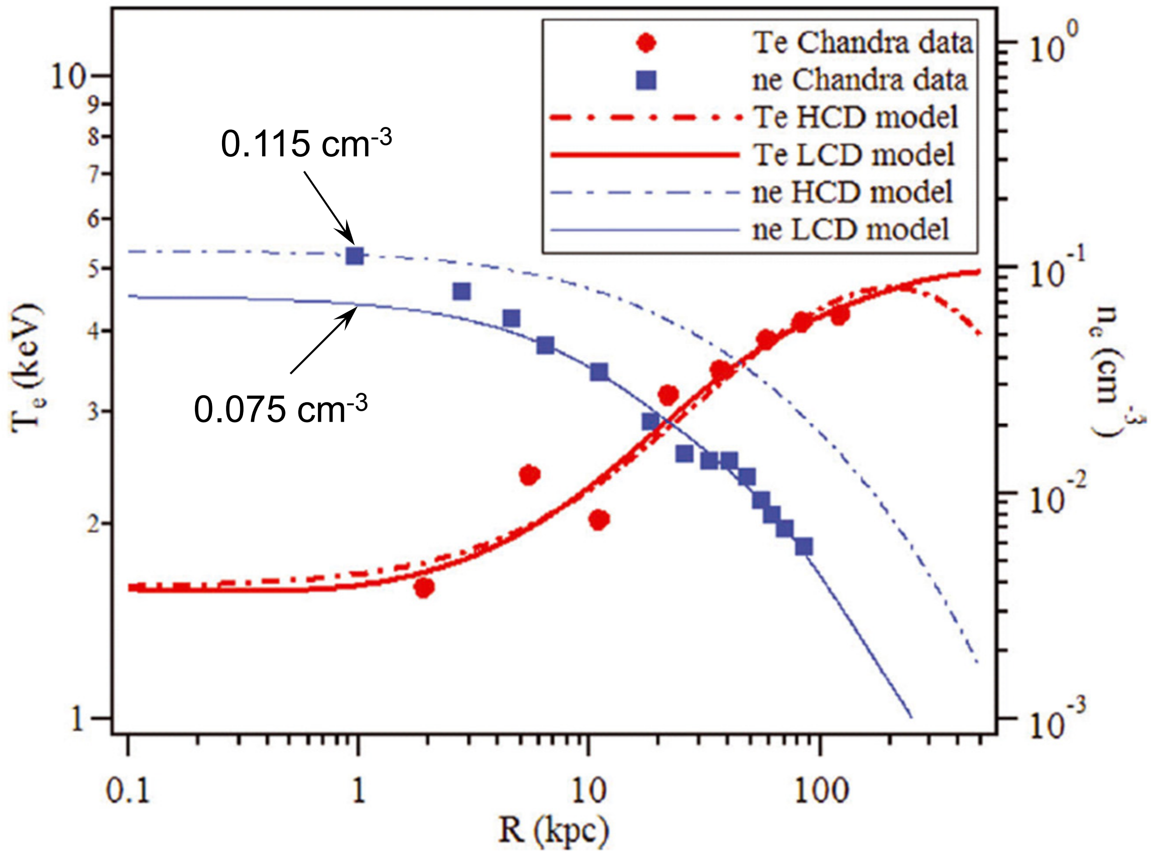
- Initial hydrostatic equilibrium strictly obeyed. Idealized radial magnetic field imposed initially.
  - ATHENA 3-D Simulations: I. Parrish, E. Quataert, and P. Sharma, ApJ, 2009
  - MACH 3-D Simulations: P. Mikellides, I. Mikellides, K. Tassis and H. Yorke, in preparation
- Discrepancies are largely due to differences in the initial conditions for n_e and T_e.



Numerical Experiments with MACH2 in 2-D Axisymmetric Geometry

- Initial conditions for A2199 as implemented in 2-D numerical tests with MACH2 [1]

$$\nabla \cdot q + \Phi_{eR} = 0 \qquad q = -f\kappa_{sp}\nabla T_e \qquad \Phi_{eR} = ac_\ell \rho \chi_P {T_e}^4$$



[1] Mikellides, I. G., Tassis, K, and Yorke, H., 2011, *MNRAS*, 410, 2602.

MACH2 simulation results underscore the sensitivity of the ICM energy balance on the initial conditions.

- 35% decrease in core density leads to a cooling catastrophe [1].

$$\tau_q \propto \frac{n_e \ell^2}{f\, T_e^{5/2}} \qquad \tau_\Phi \propto \frac{T_e^{1/2}}{n_e}$$

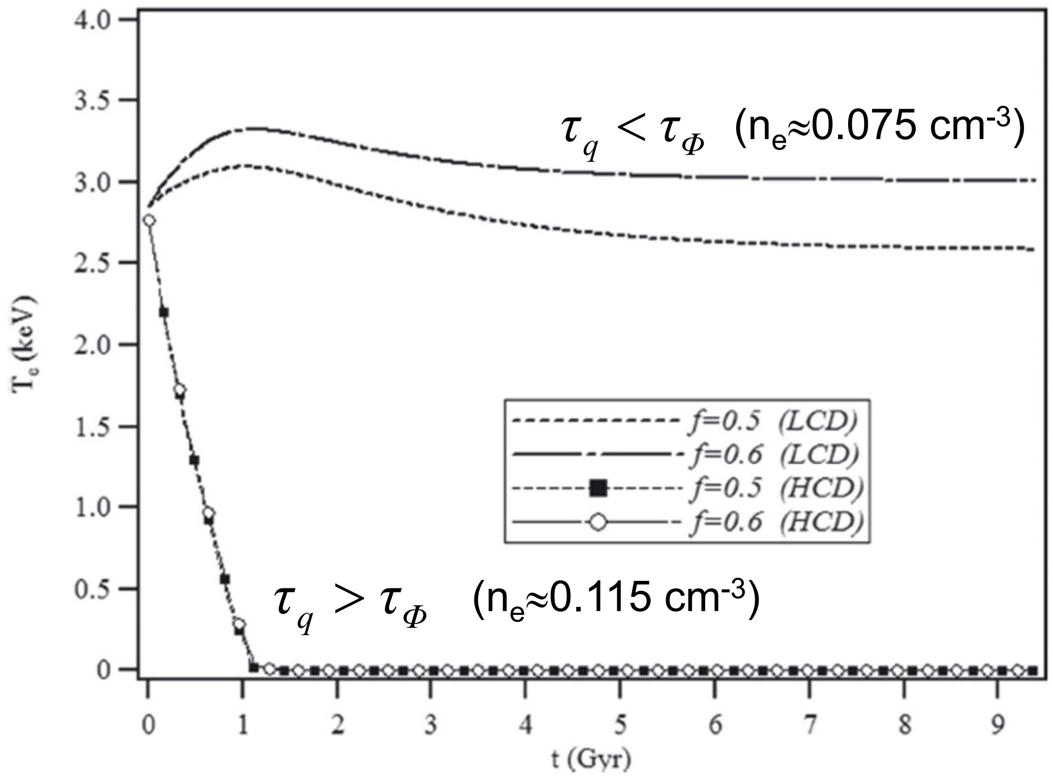
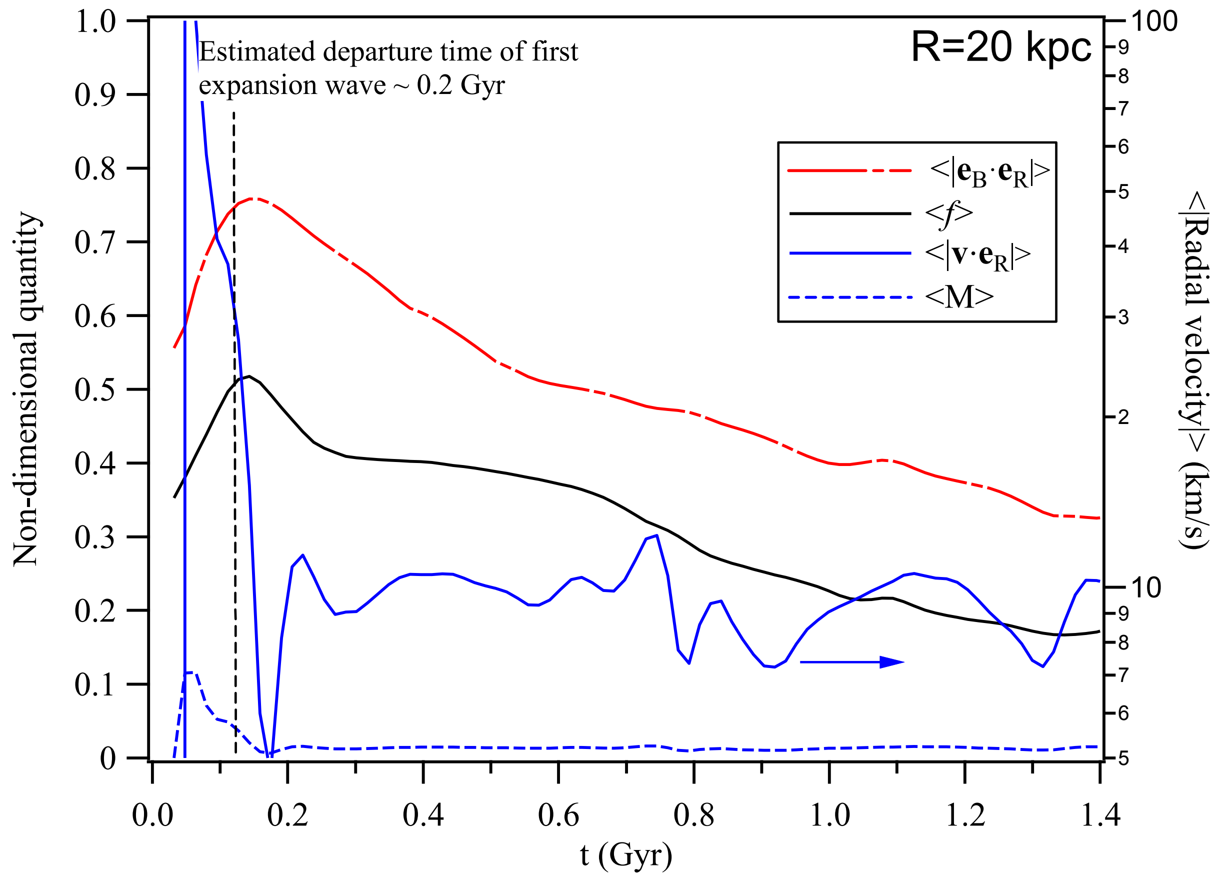


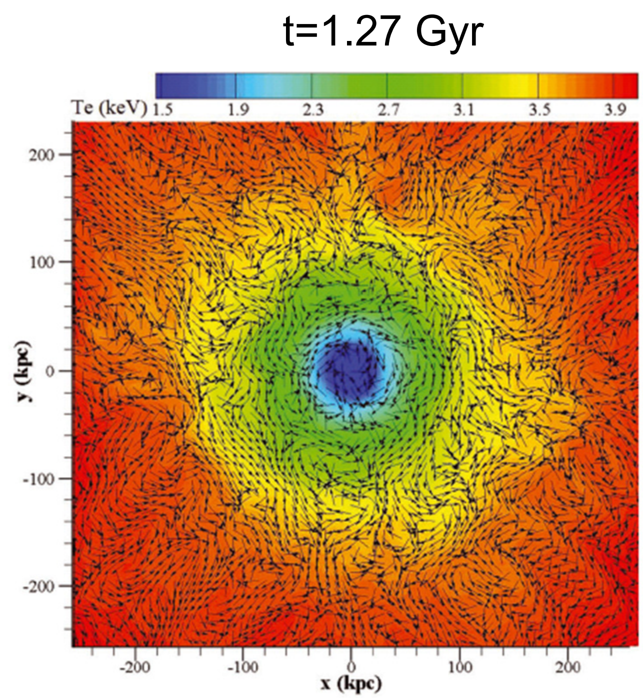
Figure 3. Results from 2D axisymmetric simulations with thermal conduction and radiation only. The solutions are plotted for different values of the heat flux factor f, at $R = 20$ kpc.

[1] Mikellides, I. G., Tassis, K, and Yorke, H., 2011, *MNRAS*, 410, 2602.

Numerical experiments with MACH2 in 2-D planar geometry seek significance of near-core hydrodynamics.

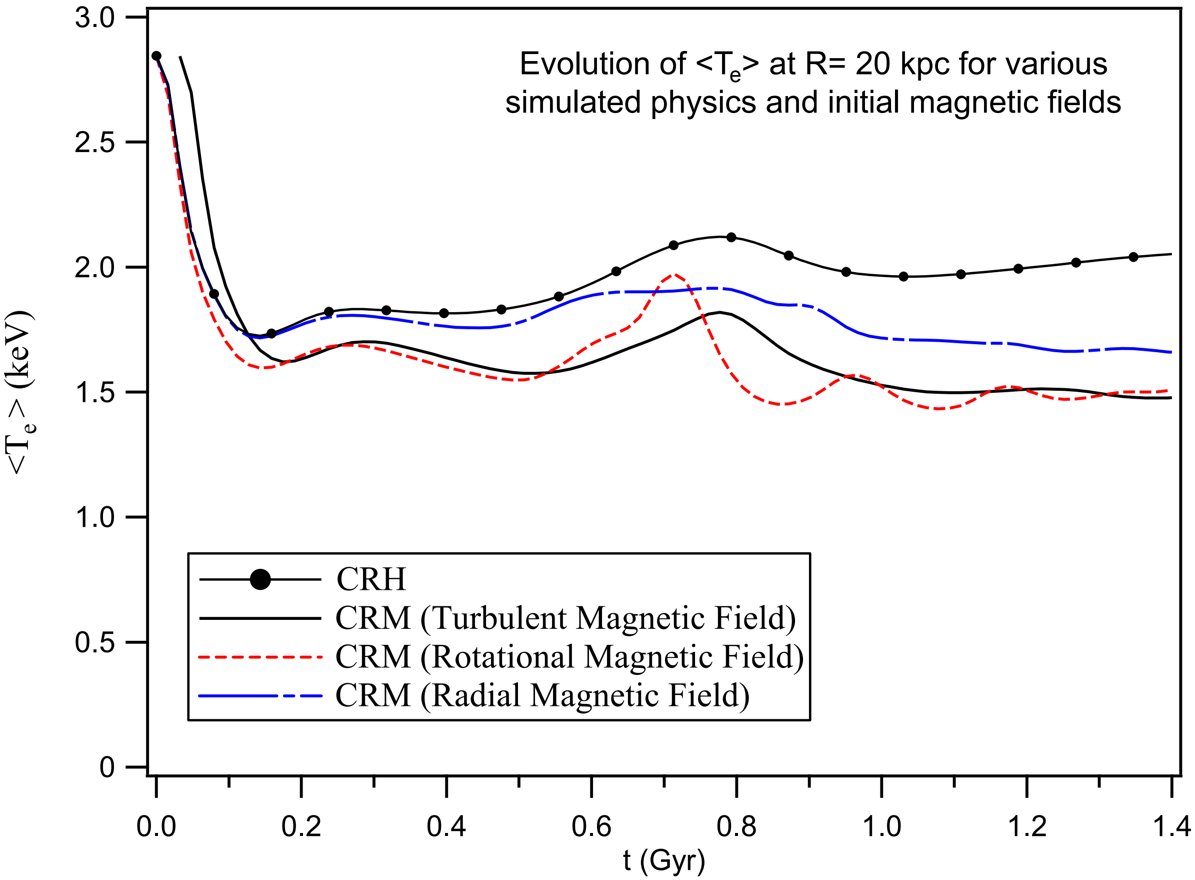
- Deviation from initial hydrostatic equilibrium deliberately imposed
- Case of turbulent initial magnetic field shown below
- During the subsonic flow rarefaction period (0.2-1.3 Gyr) effects of HBI are captured, but...





Numerical experiments with MACH2 in 2-D planar geometry expose significance of near-core hydrodynamics.

- …no cooling catastrophe occurs.
- pdV work from subsonic hydrodynamics serves as the additional energy source.



Simulation physics nomenclature: 'C' = Braginskii thermal conduction, 'R' = Radiation cooling, 'H' = Hydrodynamics, 'M' = Magnetohydrodynamics.

Summary Remarks

- MACH family of non-ideal MHD codes fully operational at JPL. ***The infusion of MACH to the astrophysics community could expand the range of problems we can address as well as the level of accuracy with which we can resolve them.***

- Necessary code augmentations to simulate 3-D MHD of ICMs in galaxy clusters completed.

- Code validation along a path of increasing level of simulation complexity:
  – reproduces published results,
  – underscores the sensitivity of the ICM evolution on the assumed initial conditions,
  – agrees with published conclusions that thermal conduction alone cannot be responsible for balancing the radiative losses; additional energy source is needed,
  – suggests subsonic hydrodynamics could play a role in the elusive energy source.

Conclusions and Future Work

- Near-core subsonic hydrodynamics found to be important in the A2199 cool-core ICM
  - High sensitivity of ICM thermal balance to the initial hydrostatic equilibrium state in numerical simulations suggests deviations from such idealized conditions in real clusters.
  - Imposed subsonic hydrodynamic wave overcame effects of HBI and prevented cooling catastrophe in 2-D MHD simulations.
  - Near-core transient “winds” possibly associated with AGN dynamical activity?
  - What is/are their effect(s)? “Stirrers” [Parrich, Bogdanović, Ruszkowski et al.] or other..?

- Plans for future work
  - All inclusive 3-D simulations of spatially- and temporally-distributed AGN bursts at the cluster center, accounting for:
    - magnetic fields of various topologies and strengths,
    - anisotropic viscous stress tensor,
    - anisotropic conduction heat flux,
    - radiation (bremsstrahlung) cooling and
    - gravity due to the dark matter and the ICM.
  - **MACH3 can account for all of the above**